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Development of a Suite of Objective Biomechanical Measurement Tools for Personal Load Carriage System Assessment

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Summary

The proper design of personal load carriage systems may be critical not only for soldier comfort, but also for soldier mobility and performance on the battlefield. Evaluation of soldier personal load carriage systems typically involves the conduct of human-based lab and field trials that can be both time-consuming and costly to conduct. Field testing usually requires multiple system prototypes of a given design iteration, with their development cost often limiting the number of design iterations tested. Human-based trials also rely on subjective opinion for system assessment. While the opinions of the ultimate users have face validity, and bias and error can be controlled in such trials, it is also desirable to have objective load carriage assessment methods and analysis tools that permit rapid analysis, design iteration and evaluation. Canada has developed biomechanical assessment and analytical tools to supplement human-based load carriage system assessment methods. This suite of tools permits efficient objective evaluation of important biomechanical aspects of load-bearing webbing, vests, packs and their components, thus contributing to early system assessment and a rapid iterative design process. This paper will introduce each of the assessment and analytical tools, their rationale, the objective measures available and the recommended performance criteria for acceptable military load carriage systems. Separate papers in these proceedings will provide the details of validation and utility of the tools that have been developed by Canada.

Introduction

Over the past several years, Canada has undertaken a research and development programme to investigate and understand the factors affecting human load carriage performance and apply that knowledge to the development of advanced load carriage systems for the soldier of the future. This research and development has been conducted by the Defence and Civil Institute of Environmental Medicine (DCIEM) through a series of contracts to the Ergonomics Research Group of Queen's University.

As this R&D programme was being launched, it became apparent that there were few tools available for the objective comparative evaluation of load carriage systems and their design features. Therefore, the aims of the research programme were fine-tuned to include the following:

- To provide a scientific basis upon which load carriage systems could be selected or designed;
- To develop and apply standardized testing methods to quantitatively evaluate load carriage system designs; and
- To optimize load carriage capacity for the soldier (not necessarily to enable them to carry more, but to allow them to carry loads more efficiently with improved performance, comfort and safety).

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Research Programme Methodology

The approach that was taken to help achieve the foregoing research aims involved the following: a thorough state-of-the-art and literature review (Pelot et al, 1995) (including identification of threshold limit values based on survival, injury and tissue tolerance data as well as a review of existing measurement methodologies); identification of those measures relevant to human comfort, tissue tolerances, and load carriage capability; investigation of methodologies suitable for the evaluation and differentiation of load carriage system and component designs; development of a suite of objective biomechanical load carriage assessment tools to augment traditional evaluation methods (Stevenson et al, 1995); validation of these tools through testing of a range of commercial and military load carriage designs using a range of measurement methodologies (Stevenson et al, 1996 & 1997c); and application of these methodologies and findings to develop recommended load carriage system performance criteria, a static biomechanical load carriage model (Stevenson et al, 1995; Pelot et al, 1998a), and a new load carriage system for the Canadian Forces (Bryant et al, 1997a, 1997b & 1997c; Reid et al, 1998, 1999a, 1999b & 1999c; Stevenson et al, 1998).

This report will provide an introduction and overview of the objective biomechanical measurement tools developed and used by Canada for load carriage system evaluation. Several other papers in these proceedings describe the validation and accuracy of these measures (Bryant et al, 2000; Morin et al, 2000), the development of performance-based load carriage system ranking criteria (Bryant et al, 2000), the development of a static model of load carriage (Pelot et al, 2000), and the use of these tools in the iterative development and evaluation of a new load carriage system for the Canadian Forces (Bossi & Tack, 2000; Reid et al, 2000a & 2000b; Stevenson et al, 2000).

Rationale for Novel Measurement and Analysis Tools

A review of scientific and technical literature (Pelot et al, 1995; Stevenson et al, 1995 & 1996) identified a range of factors known to affect human load carriage as well as a number of load carriage system evaluation methods. These methods included psycho-physical (e.g., ratings of perceived exertion, local discomfort ratings), physiological (e.g., metabolic energy cost, cardiorespiratory and other indicators of body strain), biomechanical (e.g., EMG, film analyses of posture and gait patterns, force platform measures of ground reaction forces, skin pressure) and mobility performance measures. Virtually all evaluation methods relied on human subjects carrying loads of various configuration (weight, load location, load carriage device) while performing relevant tasks (such as marching or obstacle clearance) with varying duration, distance, terrain condition and/or speed.

The psycho-physical, physiological and biomechanics measures used have been instrumental in understanding the many factors affecting human load carriage performance (i.e., load, load placement, environmental conditions, physical fitness, terrain conditions, and many other factors as reviewed by the keynote speaker at this Specialist Meeting [Knapik, 2000]). A number of measures have been sensitive enough to detect changes in load and load placement. But few, especially when considered in isolation, were considered by the authors to be effective for objectively discerning some of the more subtle design differences one finds between competing load carriage systems or between design iterations of a given system or feature.

To be of utmost value in the load carriage system design and evaluation process, the ideal measurement technique would have the following characteristics: be objective, reliable, and sensitive to subtle design differences; be related to human tolerance limits (for injury as well as discomfort, usability, and acceptability); and be applicable, easy and efficient to employ across a range of load carriage system/component designs. It is perhaps because there is no ideal single measure or approach that most assessments of load carriage systems/components have used a combination of various psycho-physical, physiological, biomechanical and task performance methods.

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Psycho-physical and subjective methods are indeed valuable for gaining insights into energy expenditure, discomfort, and feature/functionality preferences. However, they may lack sufficient sensitivity to slight design differences in suspension systems, except for perhaps the most experienced backpackers (Pelot et al, 1995).

Physiological measures can differentiate loads (Epstein et al, 1987 & 1988; Morrissey, 1988; Pierrynowski, 1981) and gross load location (Balogun et al, 1986; Haisman, 1988; Legg, 1985; Legg & Mahanty, 1985 and many other references cited by authors of papers in these proceedings), but do not appear to offer the solution for differentiating some of the more subtle design differences one finds between competing load carriage systems or between design iterations of a given system (Kirk & Schneider, 1992).

Of all the measures reviewed, biomechanics measures appeared to offer the most promise for use in an iterative design process. A measure such as skin pressure (underlying pack shoulder straps for example) has been used to differentiate pack suspension systems (Holewijn, 1990; Holewijn & Lotens, 1992; Holewijn & Meeuwsen, 2000), and is related to subjective reports of discomfort as well as tissue tolerances (Goodson & Johnson, 1981; Goslin & Rocke, 1986; Holloway et al, 1976; Husain, 1953; Sangeorzan et al, 1989). Other biomechanical factors, such as forces and moments acting on the spine (determined traditionally through gait analyses), relative distribution of load between shoulders and hips, and relative motion between payload and body (Hinrichs et al, 1982) may also be important in the objective differentiation of load carriage system designs.

Because there exist few if any physical models of human load carriage, virtually all load carriage research has been based upon experimentation using human subjects. While this is ideal for face and content validity, it may pose problems relating to reliability and logistics. Human variability demands that a range of subjects be used for testing load carriage systems. This can be time-consuming to arrange and costly to conduct, especially considering the tremendous range of design options and iterations that could be assessed. Additionally, some important measures cannot be easily measured directly (i.e., forces and moments on the spine) although these are very important in the assessment of load carriage system safety/injury potential. Finally, user opinion (properly collected to control for bias) is invaluable for assessing the utility and usability associated with specific design features and localized comfort; however, reliance on subjective comfort ratings alone for the assessment of load carriage systems would be imprudent. The development of standardized and efficient objective biomechanical test and analysis methods is therefore considered important, in order to overcome some of the limitations cited. Not only would they provide quantitative data upon which design decisions could be made, but they would also serve to shorten the design iteration and evaluation cycle and delimit the number of design options that need be subjected to more costly time-consuming human/user-based evaluation.

In summary, the literature review conducted early in the research and development programme (Pelot et al, 1995; Stevenson et al, 1995) led to the principal conclusions that biomechanics measures, together with subject perceptions, would be good indicators of design variations in the load carriage system. And because the relationship between user perceived stress under load and quantitative measurements was not very well developed there was seen to be a requirement to develop a quantifiable, repeatable measure of the ergonomic merit of a load carriage design. For these reasons, the Canadian research and development effort was directed toward the development and validation of a suite of novel biomechanical assessment and analysis tools.

Novel Biomechanical Measurement Tools

The following tools have been developed and validated (Bryant et al, 1999 & 2000; Doan et al, 1998; Morin et al, 1998 & 2000; Reid et al, 1997; Stevenson et al, 1995, 1996, 1997a, 1997b, 1997c & 1998b) in order to facilitate the objective and efficient measurement of load carriage systems. Load carriage systems and their specific components can be evaluated within only a matter of days using these tools, making them invaluable in an effective iterative design and evaluation process.

Dynamic Load Carriage Simulator

General Description. The Dynamic Load Carriage Simulator shown in Figure 1 comprises a computer-controlled pneumatic system that moves with three degrees of freedom and displaces an instrumented anthropomorphic torso through a range of vertical motion representative of human gait. It is capable of simulating a range of gaits from normal walking, running, through to routines that simulate slipping on a surface or ducking under an overhead obstacle. Vertical displacement, rotation about the anterior/posterior axis (side lean), and rotation about the medial/lateral axis (forward lean) are user programmable from a menu.

The anthropomorphic torsos built for the Dynamic Load Carriage simulator comprise a fiberglass shell and internal structure with distributed body mass that is representative of humans. Four torsos have been built to represent the 95th and 50th percentile male, and 50th and 5th percentile female (for weight, critical girth, height and breadth measurements). Body weights range from 5th percentile female (470 N) to 95th percentile male (960 N). Anthropomorphic values are based upon the US Army survey of 1988 (Gordon et al, 1989). A range of skin analogues were evaluated and Bocklite® was chosen for its force/displacement and creep properties (very reproducible and less creep than other options evaluated).

Figure 1. Dynamic Load Carriage Simulator (can be programmed to walk, jog or run and is set-up to test a load-bearing vest design)

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Outcome Measures. The outcome measures provided by the Dynamic Load Carriage Simulator include the following:

- Relative motion between payload and body in all three planes
- Forces and Moments acting upon the body in all three planes
- Skin contact pressures (both peak and average pressures)

Relative motion between payload and the body is important from a load control perspective. Payload refers not only to the load carried within a backpack, but also the contents individual pockets in a load-bearing garment. Ideally, the payload and body should move in unison in order to support stability and mobility, to minimize energy expenditure (Hinrichs et al, 1982), to avoid the potential for local tissue damage and to minimize any distraction that may be associated with the repetitive striking of payload against the body. The better load carriage system minimizes any differences in relative motion in all three axes. The Dynamic Load Carriage Simulator measures relative motion between payload and the mannequin in all three axes using the Fastrak® displacement measurement system during dynamic testing. The Fastrak® system involves a sensor (affixed to the payload of interest) which reports its displacement and orientation within a magnetic field. Outcome measures are relative motions in the X, Y and Z planes. System accuracy (RMS static = 0.66 mm, RMS dynamic = 0.65 mm) has been confirmed with the highly accurate Optotrak® system (Stevenson et al, 1996).

The measurement of forces and moments acting on the body is also critical for assessing load carriage system safety and injury prevention. There exist threshold limit values for forces to the spine at which injury can occur in all three axes (Goel et al, 1995; Waters & Rutz-Anderson, 1993). The dynamic load carriage simulator permits direct objective measurement of these forces and moments via the six degree-of-freedom load cell positioned at the height of hip joint rotation.

Skin contact pressures have been used to discern load carriage suspension system designs (Holewijn, 1990; Holewijn & Lotens, 1992; Holewijn & Meeuwsen, 2000) and are related to tissue tolerances. The contact pressures resulting from the carriage of heavy loads in poorly designed load carriage systems can result in discomfort, occlusion of blood vessels, pinching of nerves and even nerve damage (Goodson & Johnson, 1981; Holloway et al, 1976; Husain, 1953; Sangeorzan et al, 1989). The Dynamic Load Carriage Simulator permits measurement of average and peak contact pressures, and the identification of contact areas, hot spots and their sources. Average and peak skin pressures can be measured in those areas subject to contact with load carriage systems (typically shoulder, waist/hip and lumbar regions). Skin pressures are measured using the Tekscan F-Scan® pressure measurement system, shown at Figure 2, during dynamic or static testing. Average pressure refers to the average pressure across those cells triggered in a specific body region (such as anterior or posterior shoulder). Peak pressure is the highest pressure recorded for a given pressure sensel. Figure 3 shows the typical output displayed for an in-service military pack. The arrows indicate how even simple strap surface features can contribute to underlying skin contact pressures (which in this case exceeded recommended limits).

A number of tests have been performed to examine F-Scan® reproducibility, the effects of temperature, sensel usage rates and error due to sensor curvature (Morin et al, 1998; Stevenson et al, 1995). Standard errors are as follows: 9.6% of the mean for average pressure during dynamic testing; 14% of the mean for peak pressure during dynamic testing; and 9% of the mean for error due to sensor curvature. Although some studies have been conducted (Bryant et al, 1999; Morin et al, 2000; Wilson et al, 2000), research is ongoing to create calibration curves for individual sensels, to improve the accuracy of the F-Scan® system and its ability to discriminate between load carriage systems and/or components in this as well as *in-situ* applications.

Figure 2. Typical Placement of F-Scan Contact Pressure Measurement System

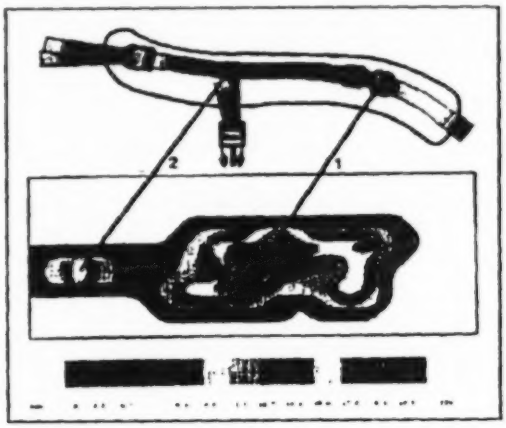

Figure 3. Typical F-Scan Output for an in-service military pack shoulder strap

Input Variables. The input variables during Dynamic Load Carriage simulator testing set-up include gait parameters (style and speed), body lean angles and pack suspension system strap tensions. The programmable simulator can be adjusted to provide pure sinusoidal motion or variations more closely approximating human gait. Speeds can also be adjusted up to 3 Hz or 5.6 km/hr.

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A six degree-of-freedom load cell is positioned in the Dynamic Load Carriage Simulator at the height of hip joint rotation. The body-fixed system measures hip reaction forces and forward lean is adjusted prior to testing so as to balance the hip moment.

Custom strap force transducers were produced so that strap tension could be used as a standardized input across load carriage systems. Strap tensions are based upon realistic tensions set by experienced pack users. Tension can be set for shoulder straps, load lifters, shoulder and hip stabilizer straps, hip belts or any other straps included in a given load carriage system design. The custom strap force transducers shown in Figure 4 comprise a link with two strain gauges mounted to measure axial force. The strap force transducers are highly accurate (+/- 2 %) and linear (R^2<0.9995) (Reid et al, 1997); however, straps must be modified sometimes to accommodate these devices. An *in-situ* strap force measurement device that does not require permanent fixation to the strap has been developed and is undergoing evaluation for accuracy and reliability.

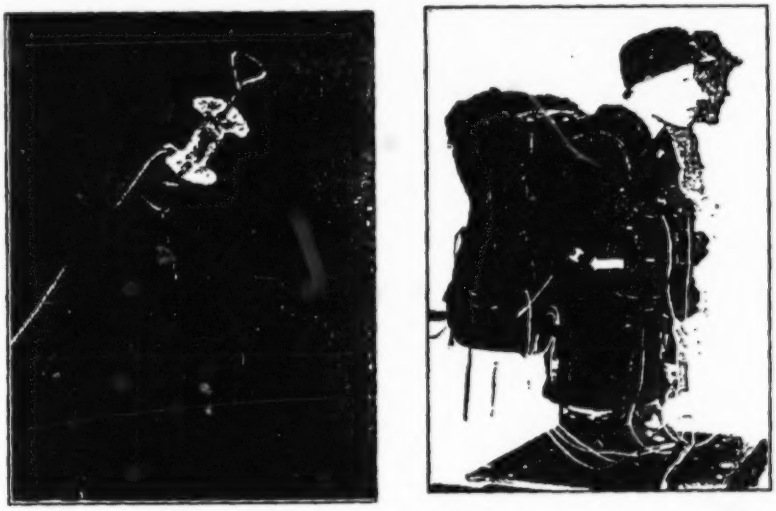

Figure 4. Custom strap force transducers for measuring strap tension.

Range of Motion (ROM) Stiffness Tester

Rationale. Restriction of the rotation of the trunk during normal gait has been shown to cause an increased energy cost (Inman et al, 1994). Furthermore, the ability to lean over is often necessary in military load carriage, for stealth, in order to avoid overhead obstructions or for crossing obstacles. Stevenson et al. (1997a) provided evidence that pack stiffness was related to soldier opinion of mobility, manoeuvrability and comfort during marching and mobility tasks. Motion restrictions in any axis may contribute to user fatigue and poor mobility performance. A Range of Motion Stiffness tester was therefore developed in order to develop objective measures of the restriction of motion caused by a load carriage system.

Description. The ROM stiffness tester is shown at Figure 5. It permits the simulation of the human motions of forward flexion, upper trunk rotation and sideways bending and the measurement of static or dynamic stiffness of a pack. The tester comprises a 50th percentile male torso (similar to that used in the dynamic load carriage simulator) that incorporates a thrust bearing (which allows trunk rotation) and a clevis hinge (permitting forward and sideways lean) at the level of hip flexion.

Outcome Measures. Once a load carriage system is fitted to the torso (using standardized representative strap tensions, as for the dynamic simulator), it is exposed to a range of rotation/bending adjustments. Motion is created by a computer-controlled motor about either the flexion/extension axis, the torsional axis or in lateral bending. Outcome measures include flexion stiffness (N/deg), torsional stiffness (N/deg), forwards and sideways bending resistance (N/deg) and break angles (deg). The angular displacement is measured by a multi-turn potentiometer and the resistance to motion is measured by strategically positioned strain gauges.

Figure 5. Range of Motion Stiffness Tester

Static Load Distribution Mannequin

A Static Load Distribution Mannequin (see Figure 6) was developed to facilitate standardized static objective biomechanical testing. The static tester is similar to the Dynamic Load Carriage Simulator except that its base is designed to sit on a 6 degree-of-freedom force platform and an additional load cell was introduced between the upper torso and hips, permitting the assessment of relative load distribution between the shoulders and hips.

The relative distribution of load between shoulders and hips is an important measure. The ability to transfer load off the shoulders onto the hips is a desirable characteristic of a backpack. Not only does this bring the load closer to the body's centre of mass, but the hips are also considered to be able to tolerate pressures more readily than the shoulders (Scribano et al, 1970, as cited in Holewijn & Meeuwsen, 2000)

The Load Distribution Mannequin has been used for answering specific pack feature design questions, such as optimal pack shoulder strap configuration (Whiteside et al, 1999), utility of lateral suspension rods in packs (Reid et al., 1999c; 2000a), and optimal attachment of the shoulder straps to the base of the pack (Reid et al, 1998; 2000b; Reid & Whiteside, 2000b). Load distribution (between shoulders and hips) has been assessed for a range of suspension system features and settings. The mannequin has also been used to develop and validate a static mathematical model of backpack load carriage (Pelot et al 1998a & 1998b) which is introduced below and described in detail in a separate paper in these proceedings (Pelot et al, 2000).

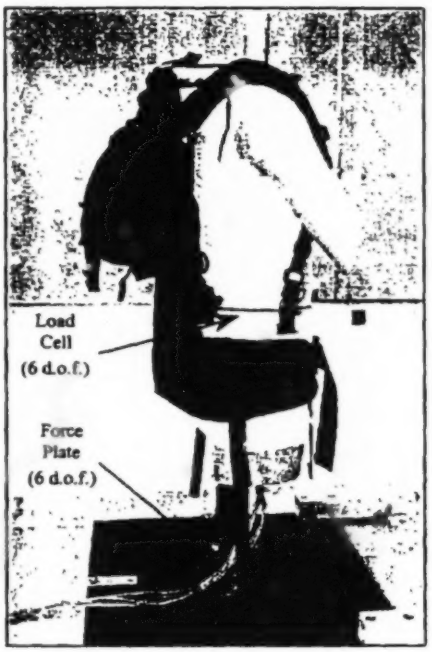

Figure 6. Load Distribution Mannequin (set-up for a study that examined shoulder strap attachment location/angle and its effect on load distribution between shoulders and hips)

Static Biomechanical Model and Analysis Tool

The static Load Distribution Mannequin was used to develop static biomechanical models of pack systems. Input values are shown at Figure 7a and include strap locations, strap angles, strap tensions, lean angle and pack weight. Model outcomes, also at Figure 7b, include the major body reaction forces associated with comfort scores on testing with human subjects, shoulder reaction forces and low back contact force. The model is based upon a simple pack with shoulder straps and hip belt. Further work is ongoing to model the impact of more advanced pack features such as load lifters, shoulder and hip stabilizer straps, lateral suspension stiffness rods, etc. Work is also underway to develop dynamic models for the future.

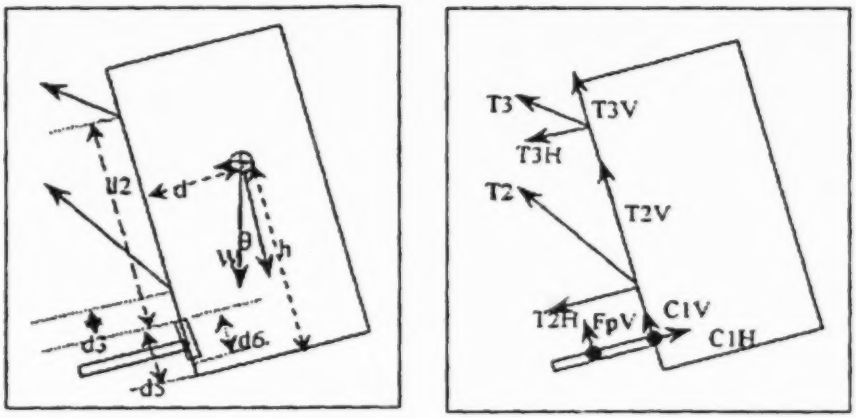

Figure 7. Static biomechanical pack model indicating input values (a-left) and outcome values (b-right)

Mobility Circuit

Despite the development of the foregoing objective measurement and analysis tools, the authors cannot stress enough how important human/user input is to the design and evaluation process. As mentioned previously, the suite of tools provides an efficient method for obtaining scientific performance data on the biomechanical properties of a given load carriage configuration. However, there are many aspects of a load carriage system that cannot be adequately addressed by biomechanics alone (especially those relating to comfort, functionality, usability). The comprehensive load carriage design and evaluation process used by Canada, therefore, included user focus groups and surveys as well as lab and field-based user trials throughout the iterative design process.

A mobility circuit has been designed and used to help validate the measures obtained from the foregoing biomechanical assessment tools. The mobility circuit presents a standardized set of tasks and movements that are representative of those that could be experienced by load carriage system users in field conditions and that permit user-based evaluations of load control and comfort. The circuit comprises a set of test stands including the following: bent and straight balance beams; boulder hop; fence climb; agility run; side slope walk; forward ramp climb; range of motion assessments; mouse hole clearance; and a range of relevant static tasks (i.e., emergency doffing, access to critical kit items, adoption of firing positions, etc). These are described in more detail in a separate paper in these proceedings (Bryant et al, 2000).

As part of the development and validation of the objective biomechanical tools and methods, and in order to be able to recommend performance-based biomechanical criteria for pack selection, a study was conducted to compare the physical measures from the new suite of tools with measures of human mobility performance and acceptability obtained during human trials across a range of load carriage systems. Results indicate strong correlation between a number of measures (Bryant et al, 2000; Stevenson et al, 1996; 1997a & 1997c) and support the validity of the objective measurement tools.

Portable In-situ Measurement System

Users vary tremendously in size, shape and preference for pack fit and adjustment, and these variances are represented to only a limited degree in the aforementioned suite of tools. Therefore, there is a desire to obtain objective measures *in-situ*, while real soldiers wear the load carriage system in question under realistic conditions. One would expect that the number of variables and strength of correlation between psycho-physical, subjective, physiological and biomechanical measures could be even higher than those established if it were possible to collect all data at the same time.

Canada is now developing an objective measurement system that can be worn by pack users during representative field tasks and permit simultaneous recording of a range of measures similar to those collected using the tool suite as well as other measures indicative of soldier performance, strain and/or comfort. The system will be used to collect data for the following purposes: to determine the most critical variables affecting load carriage performance, to further develop and validate the suite of objective biomechanics measurement and analysis tools, to assist with development of a dynamic biomechanical model, and to advance the state of knowledge regarding pack-wearer interaction.

Recommended Performance Specifications

Table 1 shows those performance-based specifications that are recommended by the literature reviewed and research conducted over the past several years. These are based upon the results of evaluations of a number of different load carriage systems (commercial and military), using a range of test methodologies (objective biomechanical tools, human mobility circuit trials), as well as injury and tissue tolerance data from the scientific literature that has been reviewed.

Table 1. Recommended performance specifications for military backpacks

Criterion	Recommended Value
Relative motion between pack and person	< 14 mm
Average skin contact pressure	< 20 kPa
Maximum continuous skin point pressure	< 45 kPa
Forces borne by the shoulders	< 290 N
Lumbar shear contact force	< 135 N

Load Carriage System Design Approach

It is suggested that the development of physical and mathematical models of load carriage will increase understanding of the factors contributing to soldier load carriage performance and also contribute to a more efficient, perhaps less costly, iterative development cycle.

Figure 8 depicts where physical and mathematical models of human load carriage might be inserted into the design process. By no means do these models intend to replace human-based testing or the requirement for interaction with end users (i.e., via focus groups, laboratory and field trials). A user-centered approach, which involves users throughout the design and evaluation process, is still strongly advocated.

Physical and mathematical models/tools can augment traditional human-based evaluation methods and permit efficient design iteration and evaluation without the need, at each design iteration, to conduct time-consuming and sometimes costly human-based trials. The suite of tools, as described in this paper, offer the ability to obtain objective performance data for a given load carriage system design, within only a matter of days of producing a prototype or design concept.

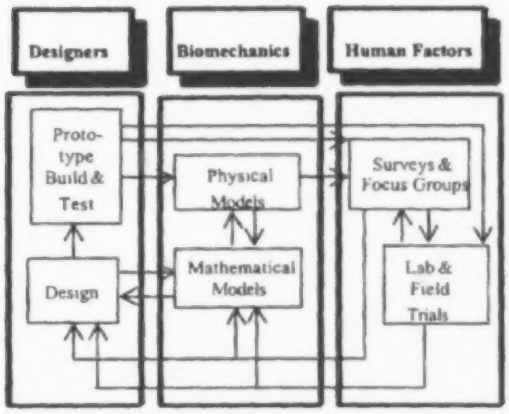

Figure 8. Canadian Load Carriage System Design Approach

With properly validated mathematical models and analysis tools, it may not even be necessary to build prototypes in order to answer some design-specific questions. If more design iterations are permitted (whether real or virtual) and objective performance data are available for system components and the system overall, one could reasonably expect that any load carriage system that is developed using these models should be much improved over those developed in the traditional manner.

This rationale and design approach was used in the development of a new load carriage system for Canadian Forces soldiers (under the Clothe the Soldier acquisition programme). The physical and mathematical models that were developed by Canada in its research programme proved to be invaluable in the design and rapid objective evaluation of a range of components comprising the new rucksack suspension system and its integration with underlying clothing and equipment layers. User focus groups and trials confirmed improvements in suspension system design and were also invaluable in the assessment and determination of pack form and function beyond those relating to biomechanics (e.g., usability, thermal characteristics, bag and modular pouch design, closure mechanisms, compatibility, soldier task performance, etc.).

The suite of tools described in this paper was used to not only assess various iterations of the new rucksack suspension system (Bryant et al, 1997b; 1997c; Reid et al, 1999b; Stevenson et al, 1998a). The aforementioned tools were also used throughout the iterative development process for the following:

- To optimize the design of the load-bearing vest shoulder straps in order to minimize pressure points when worn both alone and under the backpack (Bryant et al, 1997a; Reid et al, 1999a);
- To confirm the best vest storage pocket attachment and closure mechanisms to minimize relative motion between payload and the wearer's body (Bryant et al, 1997a);
- To determine the optimal pack shoulder strap and hip belt shape, composition and construction, to minimize pressure points and optimize forces and moments acting on the body (Whiteside et al, 1999);
- To determine the optimal shoulder strap lower attachment point and angle so that horizontal lumbar shear forces could be minimized (Reid et al, 1998; 2000a);
- To determine the efficacy and optimal integration of lateral fiberglass suspension rods in the pack for most effective transfer of load to the hips (Reid et al, 1999c; 2000a);
- To identify compatibility problems and provide scientific support to the requirement for modification of underlying clothing layers to ensure compatibility with load-bearing equipment. (Skin pressure results have led to the decision to eliminate shoulder epaulettes on the combat uniform); and

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- To contribute to the iterative design of the fragmentation protective vest by providing objective data relating to vest stiffness, compatibility with load-bearing equipment and loading of the spine (single shoulder closure versus dual symmetrical closures) (Reid et al, 2000c).

The development of the new load carriage system is described in more detail in a separate paper in these proceedings (Bossi & Tack, 2000). Other papers in these proceedings (Reid et al, 2000a; 2000b, Stevenson et al, 2000) provide results of specific testing of various iterations of the new load carriage system using the suite of objective tools described in this paper.

Future Research and Development Plans

Work is ongoing to improve the accuracy and reliability of a number of the objective biomechanical measures, specifically skin pressure measurements. Further human and simulator testing is planned for a wider range of commercial and military load carriage systems as part of the system validation process and to contribute to a better understanding of the relationship between designs and wearers. Work is ongoing to develop more advanced biomechanical models of load carriage that take into account some of the more sophisticated design features available in modern pack systems and that will consider the dynamic nature of human load carriage. Further development of an *in-situ* portable measurement device will support all of the foregoing efforts. Finally, Canada's suite of tools and design approach presented in this paper will continue to be used for the efficient objective assessment of load carriage system components, designs and underlying clothing conditions.

Conclusions

The tools described in this paper offer an efficient objective way to evaluate load-bearing clothing and equipment and their impact on users. They are intended to augment measures usually obtained with human-based testing and have already contributed to the effective iterative design and evaluation of a new load carriage system for the Canadian Forces as well as some of our allies. The suite of objective biomechanical measurement tools are on license and loan to Queen's University in Kingston, Ontario, Canada, and is available for use by both military and commercial load carriage system designers.

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